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Evaluation of Consolidation Degree from CPTu using Rahardjo (2016) Method – Case Study of Consolidating Soil in East Kalimantan

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ABSTRACT A geotechnical investigation comprised 13 CPTu and 23 dissipation testing were performed on a site in East Kalimantan due to landslide triggered by 15 to 30m thick soft clay underlying 75m high overburden embankment. The investigation covers an area of about 250m x 275m wide on the area next to the toe of the embankment. From geological map, the site situated at borders of Balikpapan Formation (Tmbp) and Kampung Baru Formation (Tpkb) with Alluvium (Qa) formation from Heliosen period nearby. Measurement from penetration showed high pore-water pressure higher than the hydrostatic pressure. Result from dissipation testing showed that the soft clay is still consolidating with residual excess pore pressure (u_f) still exist. Rahardjo (2016) Method was developed using CPTu data as its basis especially soft clay data to determine overconsolidation ratio (OCR). However, it can also be used to determine the degree of consolidation. The method uses Pore Pressure Ratio (*Bq*) value, excess pore pressure divided by net cone resistance – $Bq = \Delta u/(q_t - \sigma_{v0})$, which was obtained when performing CPTu test. The formula proposed was $1/(1.2Bq+0.1)$. The method stated that the value of Bq=0.75 equals to OCR=1 which is showing a normally consolidated clay. Bq value higher than 0.75 will show a degree of consolidation of a consolidating soil and for *Bq* value lower than 0.75 will show an OCR value of overconsolidated soil. Applying Rahardjo (2016) Method to the dissipation data performed showed an agreement on soft clay where the soil is still consolidating. However, when applied to over consolidated soil near surface this method will show a greater OCR value.

KEYWORDS Consolidating; Dissipation; Pore Pressure Ratio; Alluvium; Soft Clay; Rahardjo

1 INTRODUCTION

CPTu, cone penetration testing with pore water pressure measurement, has been widely accepted and used in the geotechnical community as one of the tools for soil investigation. Since its first introduction in the 1940s, nowadays CPTu has incorporated various sensors add-ons like geophones/accelerometer, electrical resistivity, temperature, pH, etc. (Lunne et. al., 1997, Robertson & Cabal, 2014). A CPTu testing is typically performed by pushing a probe equipped with sensors to record tip resistance (*qc*), sleeve friction (*fs*), pore pressure (*u*) and inclination (*i*) into the ground with the help of either manual or hydraulic pushing equipment. Using CPTu as investigation tool will provide continuous profile of the subsurface data (*qc*, *fs*, *u*) which can be correlated or interpreted into various soil parameter (i.e.: soil behaviour, undrained shear strength, pore pressure parameter, stress history & over consolidation ratio). CPTu is more suitable to be use in ultra-soft, very soft to soft clay material compared to performing standard penetration testing (SPT).

One useful feature of CPTu is the dissipation testing. This testing can be performed at any intended depth after pausing the penetration. Excess pore water pressure is built-up during CPTu penetration and will dissipate over time. In the dissipation testing we record the initial excess pore water pressure and its decrease over time. In sand material, the excess pore water pressure may only need short time to dissipate, while in clay it may take considerably longer time which is the reason the testing only performed until half excess pore pressure dissipated (u = 50%) (Sully & Robertson, 1999).

Overconsolidation ratio or OCR is a ratio which describe the past maximum effective consolidation stress compared to the present effective overburden stress (Robertson & Cabal, 2014). Over the years, several research has been made to obtain correlation to determine the value of OCR from CPTu. These methods were based on tip resistance, based on pore pressure, or based on both tip resistance and pore pressure (Damers & Leroueil, 2002). Research for determining OCR using pore pressure ratio (Bq) in Indonesia initially started with Setionegoro (2013) and Setionegoro & Rahardjo (2014). The research was firstly conducted using soft soil data from Jakarta area. Rahardjo (2015) and Rahardjo, et. al. (2016) later on added wider range of soil data ranging from normally consolidated to overconsolidated soil data to verify the result. This method can also be used for ultra-soft soil (Rahardjo, et. al., 2022).

2 THEORITICAL BACKGROUND

2.1 Pore Pressure Ratio

Pore pressure ratio, Bq, also known as pore pressure parameter or excess pore-water pressure ratio is the ratio between excess pore-water pressure measured during CPTu penetration to the net cone resistance. It is formulized as follows:

$$B_q = \frac{u_2 - u_0}{q_t - \sigma_{v0}} \quad (1)$$

$$q_t = q_c + u_2(1 - a) \quad (2)$$

Where:

u_2 = measured pore pressure
u_0 = hydrostatic water pressure
q_t = corrected cone resistance
q_c = measured cone resistance
σ_{v0} = vertical stress
a = net area ratio, value between 0.70 to 0.85

2.2 Dissipation Testing Curve and Interpretation

Dissipation test can be performed either on cohesive soil (clay and silt) or cohesionless soil (sand). Performing dissipation testing in clay soil often will took time for the dissipation testing reaches u_{50}. Sometimes, after hours of testing, it is still has not reached u_{50} and dissipation test should be concluded to allow continuation of the penetration until completion. There were two types of dissipation curve, which are standard (or monotonic) and dilatonic. Typical dissipation test curve for both type is presented in Figure 1.

General method for interpretation of dissipation test was log-time and square root-time (Sully et. al., 1999). However, sometimes data obtained from field needs to be corrected. Correction method using time shifting method for dilatonic dissipation curve was proposed by Sully et. al. (1999) with study from Cai et. al. (2012) showed that when using this method, the t_{50} should be corrected by subtracting the t_{50} with $t_{u\text{-}max}$ (time needed from initial dissipation test to maximum pore pressure) and rigidity index. Method to overcome drawback from short dissipation testing ($u<u_{50}$) is to use inverse time method (Lim et. al., 2014) and inverse square root time method (Liu et. al., 2014).

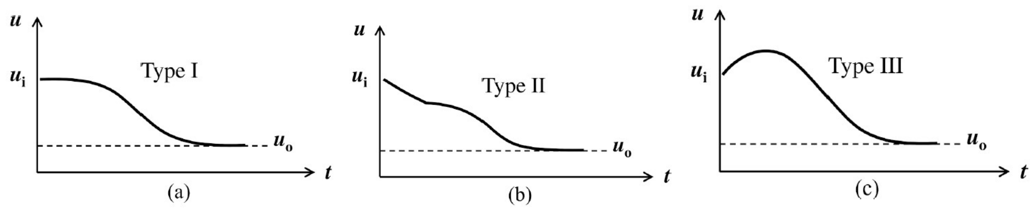


Figure 1. Types of Dissipation Curves (Type I: Standard; Type II & III: Dilatory (Lim, Y.X et. al., 2018)

2.3 Residual Excess Pore Water Pressure

During the dissipation testing in a normally consolidated soil, the excess pore-water pressure will dissipate and the pore-water pressure will eventually become hydrostatic water pressure at final dissipation (u=100%, $u=u_0$). However, in a consolidating soil, the value will be higher than hydrostatic water pressure as it contains residual excess pore-water pressure (u_f) (u=100%, $u=u_f$) (Lim et. al., 2014; Liu e. al., 2014; Rahardjo et. al., 2016). This can be formulated as follows:

$$u_2 = u_0 + \Delta u + u_f \tag{3}$$

Where:

u_2 = measured pore pressure
u_0 = hydrostatic water pressure
Δu = excess pore-water pressure
u_f = residual excess pore-water pressure (value = 0, in NC soil)

In the inverse time and inverse square root time method, the end parts of the dissipation time were plotted against pore pressure. The plotted value will show a linier trend line. Extrapolating this linier trend line to intercept the pore pressure axis will show the u_{100} value. Lim et. al. (2014) and Liu et. al. (2014) study shown that the intercept for under consolidating soil will be above the hydrostatic value (u_0) which is showing the residual excess pore pressure (u_f) and for normally consolidated and overconsolidated soil, the intercept will be at u_0 or below u_0.

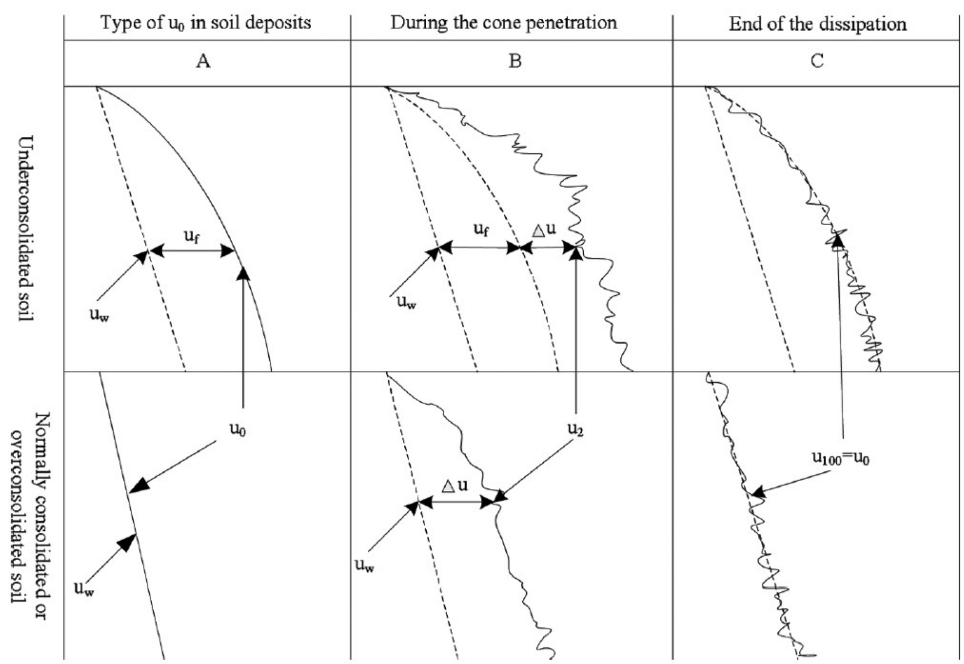


Figure 2. Difference of Dissipation Testing in Consolidating, Normally Consolidated and Overconsolidated Soil (Liu et. al., 2014)

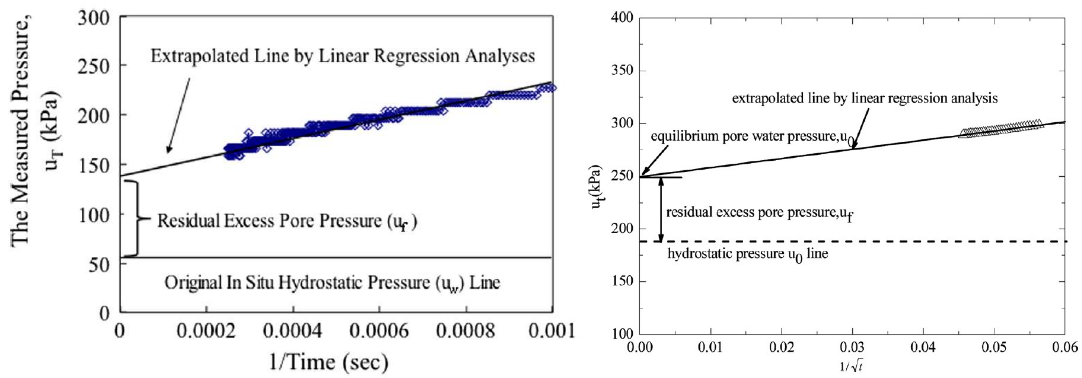


Figure 3. Inverse Time Method (Lim, et. al., 2014) and Inverse Square Root Time Method (Liu et. al., 2014)

3 RAHARDJO (2016) METHOD FOR OBTAINING OBTAINING OVERCONSOLIDATION RATIO (OCR)

The Rahardjo et. al. (2016) method showed that the value of 1.0 (normally consolidated soil) correspond to 0.75 *Bq* value. The value below 1.0 shows the degree of consolidation while the value greater than 1.0 shows the OCR. Since the *Bq* value obtained continuously during CPTu penetration, the degree of consolidation the soil can be profiled using Rahardjo (2016) since ground surface until the end of penetration. The correlation between *Bq* and OCR was proposed by using the following formula:

$$U \text{ or } OCR = \frac{1}{1.2.\mathrm{Bq}+0.1} \tag{4}$$

Where:

U = degree of consolidation

OCR = overconsolidation ratio

B_q = pore-water pressure ratio

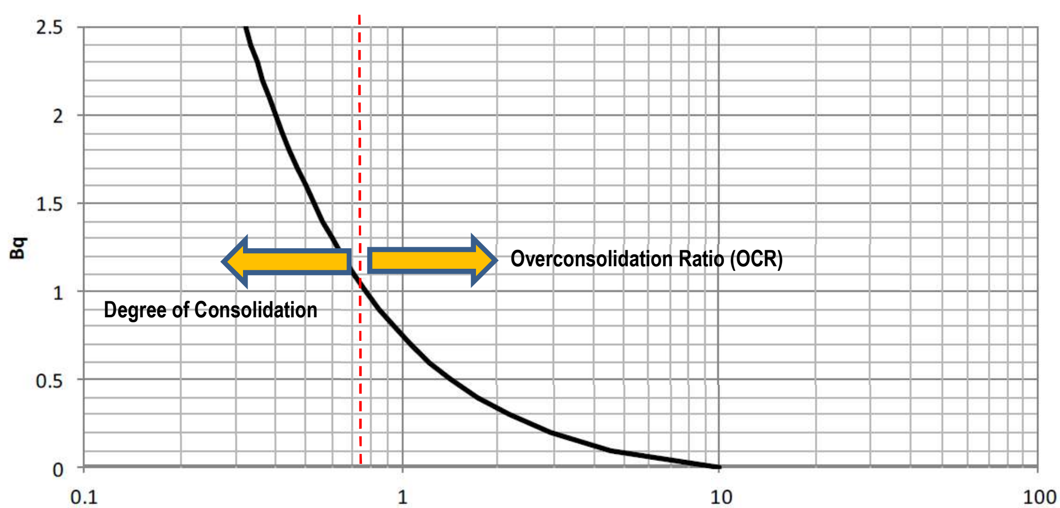


Figure 4. Rahardjo et. al. (2016) Method

4 KULHAWY & MAYNE (1990) METOD FOR OBTAINING OVERCONSOLIDATION RATIO (OCR)

To compare with Rahardjo (2016) method, author used a widely known relationship between OCR and *Qt* which was proposed by Kulhawy & Mayne (1990) as follows:

$$OCR = k.Q_t \tag{4}$$

$$Q_t = \frac{q_t - \sigma_{v0}}{\sigma'_{v0}} \tag{5}$$

Where:

Qt = normalized cone resistance
q_t = corrected cone resistance
σ_{v0} = vertical stress
σ_{v0}' = effective vertical stress
k = ranging from 0.2 to 0.5, average value 0.33

The formula presented in equation (4) have a limitation usage which valid for Qt <20. The value of k will depend with the age of clay material. Higher value should be taken if the clay material has higher age. Li et. al (2016) showed the average value of k=0.32. The Kulhawy & Mayne (1990) method was chosen as comparison to the the Rahardjo (2016) method as this method was derived from also from CPTu and shows continuous value.

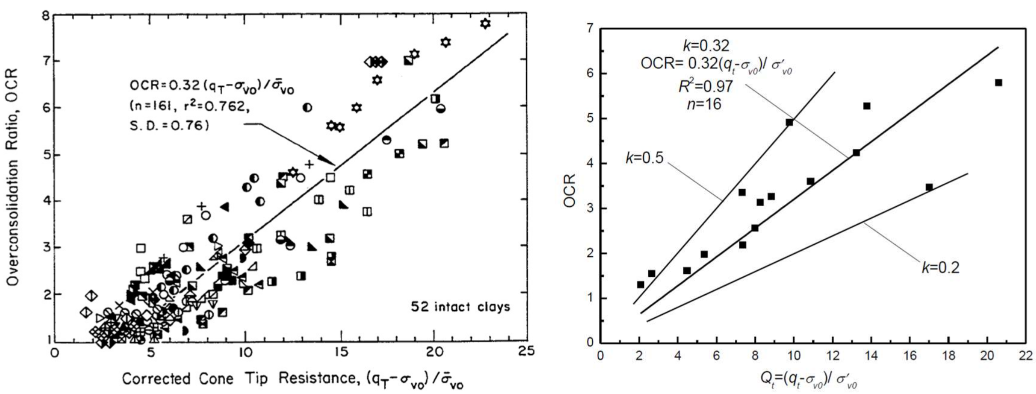


Figure 5. Overconsolidation Ratio relationship with Qt from CPTu (Kulhawy & Mayne, 1990) (Left) and Li, et. al. (2016) (Right)

5 DATA AND ANALYSIS

5.1 Site Information

The site is located in East Kalimantan. The site is relatively flat and was situated in a borderline of Balikpapan Formation (Tmbp) and Kampung Baru formation (Tpkb) with Alluvium Formation (Qa) from Heliosen period nearby in the east side as shown in Figure 6. In this area, a coal mine concession and oil & gas pipeline right of way (ROW) was located side by side with the former on the left side while the latter on the right side. An overburden waste dump was built up to 75m RL with distance from 2km up to 200m from edge of ROW between 2010 and 2016. In 2016, a ground movement occurred in the ROW causing a shift in one of the pipelines in the area. The shifted pipeline was moved to 6.8m horizontally and thrusted upwards to 2.0m high. Subsequent geotechnical investigation revealed that the overburden waste dump was built underlying a 15 to 32m thick soft clay beneath which causes a long distance excess pore water pressure migration and finally causing shifting in the pipeline.

Figure 6. Geological Map of Site Location (Left)

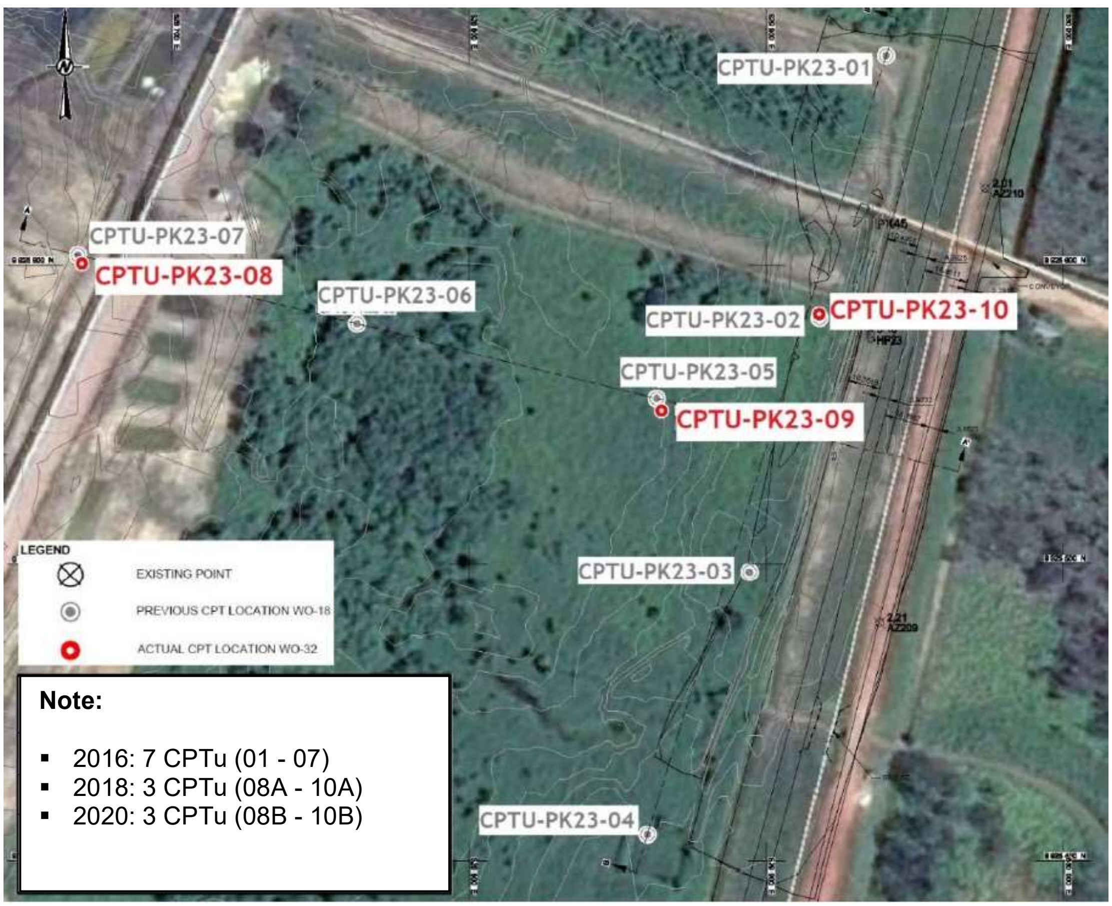


Figure 7. Layout of Geotechnical Investigation (Right)

5.2 Geotechnical Investigation

CPTu penetration with dissipation testing performed at three different occasions. The timeline for the investigation is breakdown as follows:

- The first geotechnical investigation performed between August and September 2016 consisted 7 CPTu and 12 dissipations (CPTu-01 to CPTu-07)
- The second geotechnical investigation carried out between June and July 2018 consisted 3 CPTu and 4 dissipation testing (CPTu-08A to CPTu-10A)
- Prefabricated Vertical Drain (PVD) installation between October and November 2019
- The last geotechnical investigation performed on February 2020 consisted 3 CPTu and 7 dissipation testing (CPTu-08B to CPTu-10B)

A total of 14 CPTu and 23 dissipation testing were performed over 4 years' period, however, not all data can be retrieved / downloaded due to corrupt data (penetration data corrupted for CPTu-08A, 09A and 10A while dissipation data corrupted for CPTu-08B and CPTu-10B). The location of the testing is shown in Figure 7 while details of testing presented in Table 1. The investigation in 2016 showed high excess pore water pressure which later on considered as the reason of the landslide. Countermeasure with installing pre-fabricated vertical drain (PVD) to reduce the excess pore pressure was implemented in October to November 2019. The CPTu and dissipation performed in 2018 and 2020 was intended to measure the excess pore pressure before and after PVD installation.

Table 1. Summary of CPTu Dissipation Testing

CPTu ID	Elevation [m]	GWL [m]	Dissipation Depth [m]	Duration [s]	Bq [%]	u_i [kPa]	u_0 [kPa]
CPTu-01	6.65	0.0	3.91	3799	0.44	139.70	31.78
			12.50	362	1.78	301.30	122.63
			27.92	2908	1.31	743.50	267.32
CPTu-02	6.62	2.0	9.18	11340	1.00	208.00	70.44
			31.34	3600	0.57	883.70	287.83
CPTu-03	6.24	4.0	4.11	10500	0.17	95.583	1.08
			6.76	3327	0.42	165.32	27.08
			9.90	8580	0.68	250.17	57.88
CPTu-04	4.55	1.0	12.63	8460	0.89	378.87	114.09
CPTu-05	8.13	1.5	15.11	10080	1.25	330.20	133.51
CPTu-06	11.09	4.0	18.72	9210	2.48	361.10	144.40
CPTu-07	12.32	2.0	22.27	9210	1.08	529.10	198.05
CPTu-08A	12.86	2.0	21.55	8130	1.30	531.82	191.78
CPTu-09A	8.47	0.0	15.2	14850	1.60	337.64	149.11
CPTu-09B	7.79	2.40	3.51	2160	0.31	137.0	55.0
			8.86	4350	0.27	236.0	162.0
CPTu-10A	5.64	0.0	9.73	11130	0.90	215.19	95.45
			30.59	2340	1.00	692.39	300.09

5.3 Dissipation Interpretation

Dissipation testing was interpreted using the inverse time and inverse square root time with time is in second. Only 18 dissipation testing from 23 performed was usable. Figure 8 shows the result from dissipation testing a CPTu-02 for 9.18m depth. At this depth, both the inverse and the inverse square root time method showed that the extrapolated line u_{100} above the hydrostatic water pressure which means there is a residual excess pore pressure.

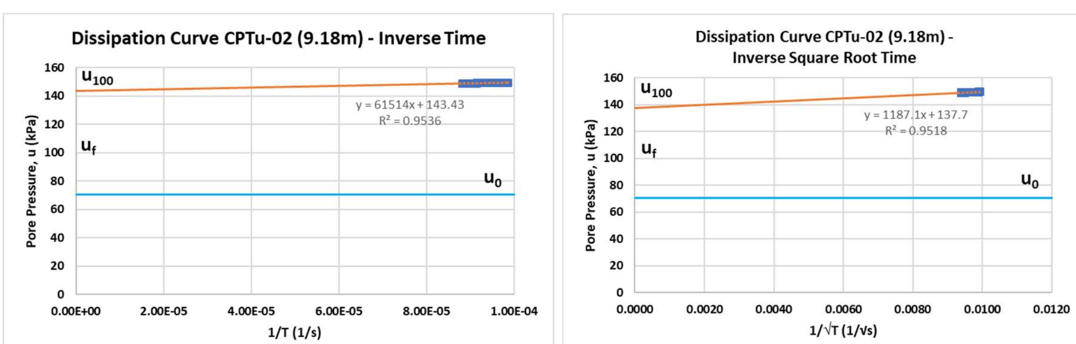


Figure 8. Residual Excess Pore-Water Pressure from CPTu-02 for dissipation at depth 9.18m

The interpreted dissipation curve for CPTu-02 at 31.34m depth showed the extrapolated line intercepts the pore pressure almost similar with the hydrostatic pressure value for inverse time and below the hydrostatic water pressure for inverse square root time method. This means there is no residual excess pore-water pressure and therefore indicates that the soil is not consolidating. Table 2 presents the results of dissipation interpretation.

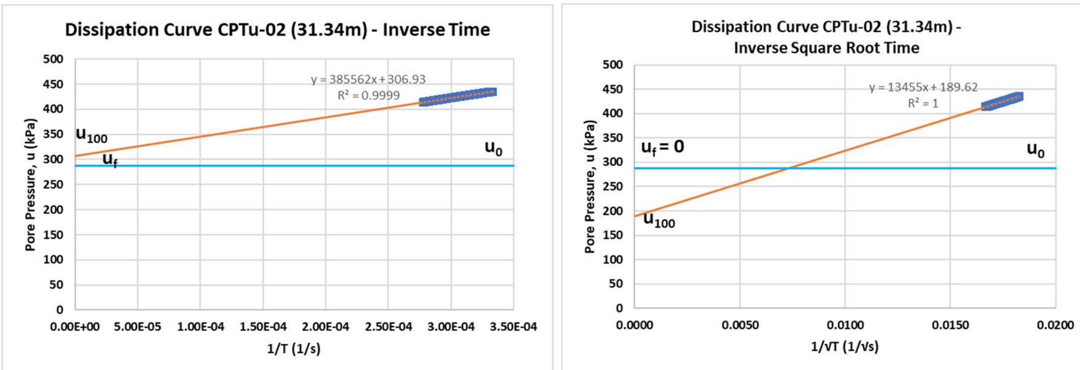


Figure 9. Residual Excess Pore-Water Pressure from CPTu-02 for dissipation at depth 31.34m

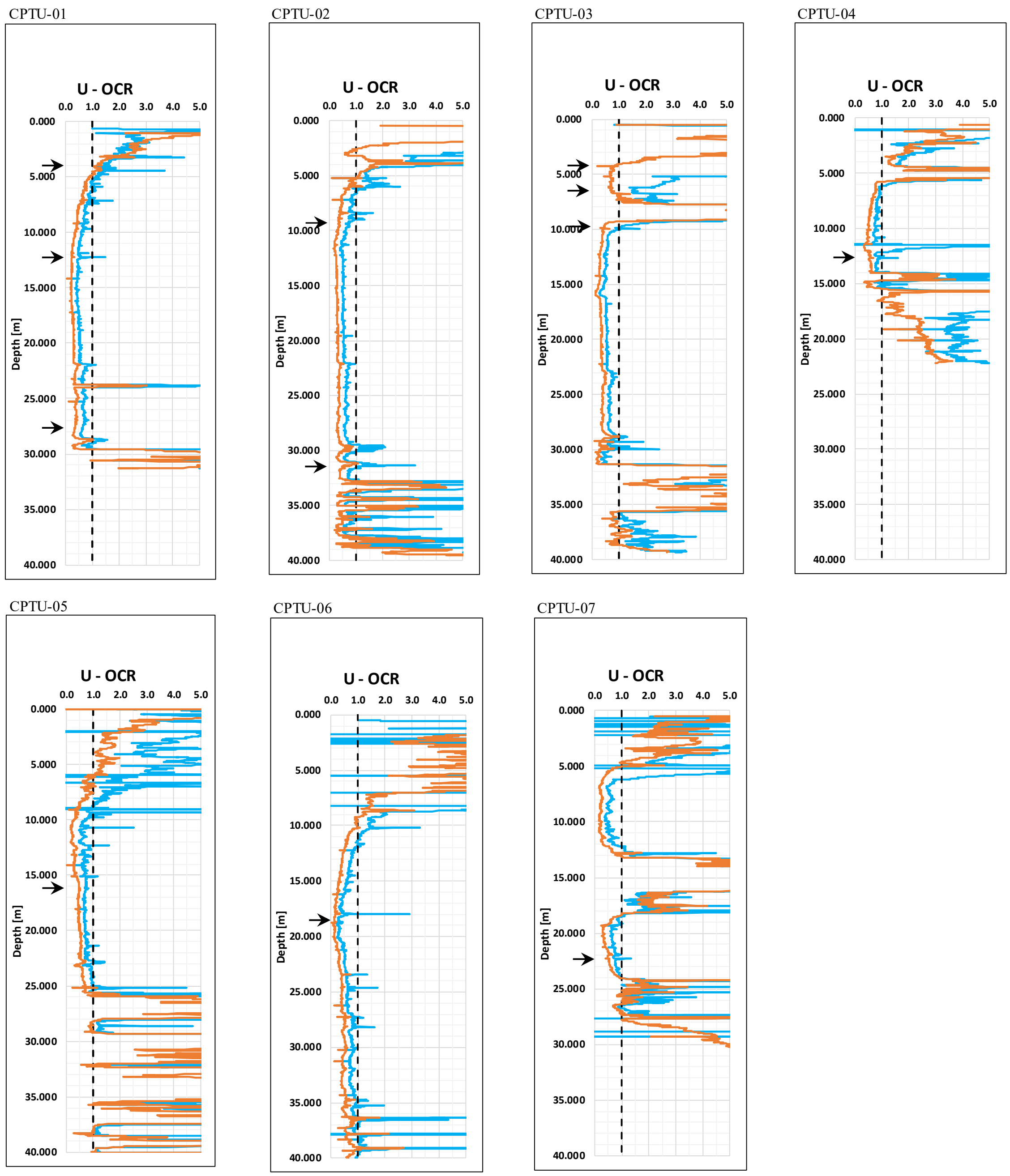
Table 2. Dissipation Testing Interpretation

CPTu ID	Test Information			Inverse Time Method		Inverse Square Root Time Method		Remarks
	Depth [m]	GWL [m]	u_0 [kPa]	u_{100} [kPa]	u_f [kPa]	u_{100} [kPa]	u_f [kPa]	
CPTu-01	3.91	0.0	31.78	20.03	0	0.00	0	No excess PWP
	12.50		122.63	264.03	141.40	252.31	129.69	With Residual Excess PWP – Still Consolidating
	27.92		267.32	429.10	161.78	337.41	70.09	With Residual Excess PWP – Still Consolidating
CPTu-02	9.18	2.0	70.44	143.43	72.99	137.70	67.26	With Residual Excess PWP – Still Consolidating
	31.34		287.83	306.93	19.10	189.62	0	No excess PWP
CPTu-03	4.11	4.0	1.08	69.12	68.04	61.97	60.89	No excess PWP
	6.76		27.08	78.49	51.41	65.39	38.31	With Residual Excess PWP – Still Consolidating
	9.90		57.88	123.70	65.82	106.28	48.40	With Residual Excess PWP – Still Consolidating
CPTu-04	12.63	1.0	114.09	159.96	45.87	113.19	0	Both Method Contradicts
CPTu-05	15.11	1.5	133.51	246.20	112.69	230.90	97.39	With Residual Excess PWP – Still Consolidating
CPTu-06	18.72	4.0	144.40	324.52	180.12	319.93	175.53	With Residual Excess PWP – Still Consolidating
CPTu-07	22.27	2.0	198.05	348.23	149.38	313.76	114.91	With Residual Excess PWP – Still Consolidating
CPTu-08A	21.55	2.0	191.78	332.34	140.56	292.76	100.98	With Residual Excess PWP – Still Consolidating
CPTu-09A	15.2	0.0	149.11	232.00	82.89	213.57	64.46	With Residual Excess PWP – Still Consolidating
CPTu-09B	3.51	2.40	55.0	62.23	27.80	36.99	2.56	With Residual Excess PWP – Still Consolidating
	8.86		162.0	131.71	44.79	98.51	11.59	No excess PWP
CPTu-10A	9.73	0.0	95.45	143.80	48.35	131.47	36.02	With Residual Excess PWP – Still Consolidating
	30.59		300.09	440.22	140.13	346.97	46.88	With Residual Excess PWP – Still Consolidating

Based on the interpretation of the performed dissipation testing, the u_{100} showed higher value compared to the u_0 in most of the interpreted result which means there is still residual excess pore water pressure therefore showing that the soil is still in consolidating stage.

5.4 Result & Comparison

After confirming that the soil is still consolidating from dissipation interpretation, both Rahardjo (2016) and from Kulhawy & Mayne (1990) method then used to provide continuous value of degree of consolidation and OCR value as both methods were based on the CPTu data. Results from both methods then plotted, overlaid together for comparison and presented in Figure 10 using k =0.3. The value of U-OCR=1 shown in the graphs means U=100% and OCR=1 value. The results showed that the value of OCR obtained from Kulhawy & Mayne (1990) smaller than U-OCR obtained from Rahardjo (2016) method.



Note: Penetration data for CPTu-08A, 09A and 10A corrupted

Legend: Rahardjo (2016) Kulhawy & Mayne (1996) ---- U-OCR Line → Dissipation Test Location

Figure 10. Comparison of U-OCR using Kulhawy & Mayne (1990) using *k* = 0.3 and Rahardjo (2016) Method

Revising the value of k = 0.5 resulting both graphs showing similar results for consolidating soil layer which is soft clay. However, for the overconsolidated layer, there is no conclusive result obtained for both methods. Based on the information provided, the value of k = 0.5 indicates the clay layer should be of higher age. This value contradicts with data from geological map which indicated Qa formation is considered a young age soil.

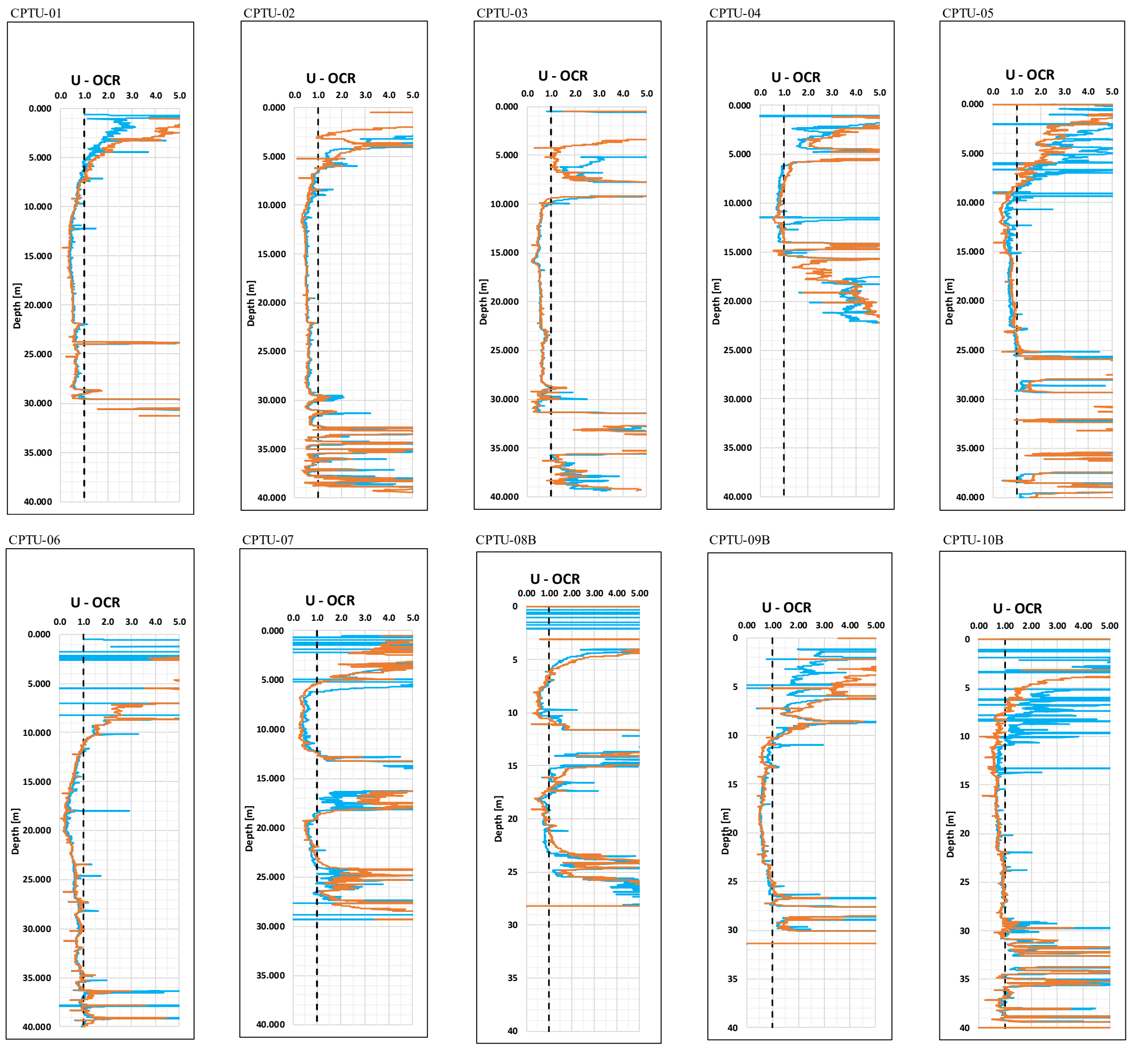


Figure 11. Comparison of U-OCR using Kulhawy & Mayne (1990) using $k = 0.5$ and Rahardjo (2016) Method

6 SUMMARY & CONCLUSION

The following conclusions were derived based on the result and comparisons:

- Dissipation interpretation for determining the residual excess pore water pressure using inverse time and inverse square root time generally showing similar result with inverse square root time having smaller value of the two. The appearance of residual excess pore pressure is an indication of the soil is in consolidating stage.
- Result from dissipation interpretation is in line with result from Rahardjo (2016) method which indicates the soil is in consolidating stage.
- When using the k=0.3 value, Kulhawy & Mayne (1990) method showed lower value result compared to the Rahardjo (2016) method. The k=0.3 is slightly lower than suggested average value of 0.32 and 0.33.
- The value of Rahardjo (2016) method will be similar to Kulhawy & Mayne (1990) method when using k=0.5 (which is upper bound). The k=0.5 value indicates that the soil is of higher age which contradicts with the Qa formation from Heliosen period (young age alluvium).
- When using either k=0.3 or k=0.5 value to compare Kulhawy & Mayne (1990) with Rahardjo (2016), inconclusive result was found in the upper layer soil where it is not consolidating. This suggested opportunities for further research for normally consolidated and overconsolidated soil using Rahardjo (2016) method.

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